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ICT Asset Prices: Marshaling Evidence into New Measures

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ICT Asset Prices:
Marshaling Evidence into New Measures

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Abstract

This paper is a companion to our recent paper, "ICT Services and their Prices: What do they tell us about Productivity and Technology?" It provides the sources and methods used to construct national accounts-style price deflators for the major components of ICT investment—communications equipment, computer equipment, and software—that were analyzed and used in that paper. The ICT equipment measures described herein were also used in Byrne, Fernald, and Reinsdorf (2016).

Keywords: Information and Communication Technology (ICT); ICT asset prices; Price measurement.

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1 Introduction

National accounts-style research price indexes for information and communication technology (ICT) assets have been used and analyzed in recent works (Byrne and Corrado, 2017; Byrne et al., 2016). The sources and methods used to construct these prices are documented and described in this paper. The table below, reproduced from Byrne and Corrado (2017), reports these new price indexes.

The primary approach used to construct the ICT price indexes shown below was to take stock of existing literature on high-tech price change. Although much of our own new work also is introduced, the emphasis is on integrating available information into existing measures. The evidence marshaled suggests official ICT prices suffer from substantial mismeasurement. As the discussion in Byrne and Corrado (2017) highlighted, ICT has entered a new era in which mobile and cloud platforms are becoming the predominate means organizations use to interact with both customers and employees, and skepticism abounds as to whether statistical agencies are capturing all that is going on. The new ICT asset prices in fact suggest a rapid pace of change. That said, many types of ICT products have not been studied or examined in-depth for many years—or ever in the case of enterprise systems software and newer types of enterprise applications (e.g., "business intelligence apps")—which strongly suggests new work and new evidence are needed to better assess all that may be going on.

There are three sections in this paper, one corresponding to each major component of ICT investment—communications equipment, computers and peripherals, and software.

Table 1: **ICT Investment Price Change (annual rate)**

		1963 to 1987 (1)	1987 to 2004 (2)	2004 to 2015 (3)	1994 to 2004 (4)	2004 to 2008 (5)	2008 to 2015 (6)
1.	**ICT investment**	-4.9	-10.6	-8.0	-12.4	-8.9	-7.5
2.	Communication equipment	.4	-7.3	-8.7	-9.1	-7.4	-9.5
3.	Telecom	-.3	-11.7	-12.4	-14.3	-10.1	-13.7
4.	Other equipment	.4	-8.3	-9.3	-10.3	-8.1	-10.0
5.	Capitalized services	–	1.1	-3.7	-.1	-2.5	-4.3
6.	Computers and peripherals	-17.1	-21.2	-17.0	-24.0	-21.8	-14.1
7.	Servers and storage	-18.1	-25.2	-25.7	-31.0	-30.6	-22.7
8.	PCs	–	-27.9	-23.4	-30.3	-30.2	-19.2
9.	Other equipment	-9.0	-9.3	-3.3	-8.8	-5.4	-2.0
10.	Capitalized services	–	-2.0	-2.2	-3.1	-1.5	-2.6
11.	Software	-1.0	-4.4	-3.9	-5.5	-3.5	-4.1
12.	Prepackaged	-9.8	-9.0	-7.0	-9.6	-6.8	-7.2
13.	Custom and own-account	.0	-2.0	-2.2	-3.1	-1.5	-2.6
Memos:							
14.	ICT excluding PCs	-4.5	-8.4	-6.5	-9.9	-6.6	-6.4
15.	Computers excluding PCs	-16.6	-17.1	-11.6	-19.8	-14.5	-9.9
16.	BEA ICT	-2.7	-6.4	-2.1	-7.5	-3.3	-1.4
17.	BEA ICT excluding PCs	-2.6	-4.5	-1.4	-5.2	-1.9	-1.2
18.	Computers excluding PCs	-16.6	-11.0	-3.6	-12.7	-6.6	-1.8

NOTE: Figures reported as "BEA" are authors' calculations based on BEA data.

2 Communication Equipment

The primary source for this index is Byrne and Corrado (2015a,b), who developed prices for many of the detailed products of the communications equipment manufacturing industry (NAICS 3342). Byrne and Corrado (2015a) also reviewed the extensive literature that has studied technological developments in telecommunications equipment.

The U.S. BEA's detailed commodity composition of communications equipment investment is reproduced in the figure shown on page 3. The table is structured according to I-O item codes, which largely align with NAICS industry codes. As may be seen, communication equipment investment has both equipment and capitalized services commodity types, and the equipment components include other NAICS 334 industries, notably, audio and video equipment manufacturing (NAICS 3343) and search, detection, and navigation equipment manufacturing (NAICS 3345).

Price indexes and shares for each relevant equipment component, as well as for the capitalized services components, are needed to obtain an overall price index for communications equipment. The estimated rates of change for these price indexes are shown in the table on page 4, and shares of the key components in total communication equipment investment are shown in the figure on page 5. A description of the derivation of these estimates follows.

2.1 Equipment components

To build a new price index for communication equipment investment, the equipment components are grouped into four types (some very small items are ignored):

- telecommunications and data networking equipment (line 4 plus lines 14–18)
- audio/video equipment (line 23)
- broadcasting and other communications systems (lines 12–13)
- search & navigation equipment, nondefense (line 26)

The telecommunications and data networking equipment grouping captures systems enabling two-way communications, a classification scheme the authors developed for measuring the products of the communications equipment manufacturing industry (NAICS 3342) in earlier work (Byrne and Corrado, 2015a, table 1, page 7). The broadcasting and other communications systems grouping is the industry's one-way systems.

Telecommunications/data networking equipment. Telecommunications and data networking equipment (hereafter telecom equipment) is the major component of communication equipment investment (see figure 2), and its price index is an important driver of estimated price change for other equipment components (except A/V). Table 2 in Byrne and Corrado (2017) showed some of the more dynamic products of the communications equipment industry, but all told, Byrne and Corrado (2015a) estimated constant-quality spending price indexes for 14 major product lines of the industry based on item-level price indexes for about 150 individual products. Comprehensive coverage began in 1963.

Two modifications are made to the Byrne-Corrado NAICS 3342 spending price index before including it in the communications equipment investment price index constructed for this paper. First, the contribution of consumer purchases of cell phones and terminal equipment (telephone handsets, telephone

Figure 1: **Commodity Composition of Communication Equipment Investment**

	I-O item code	Equipment by type of product	2007 Value (millions of dollars)
1		**Communication equipment**	**106,169**
2	**33411A**	**Computer terminals and other computer peripheral equipment manufacturing**	339
3		Computer terminals (excl. parts/attachments/accessories/etc.)	
4	**334210**	**Telephone apparatus manufacturing**	20,652
5		Telephone switching equipment	
6		Carrier line equipment & nonconsumer modems	
7		Telephone sets, including wireless phone sets, exclude cell phones	
8		Wireline voice equipment	
9		Data communications equipment (including routers, gateways, bridges, terminal servers, and concentrators)	
10		Telephone apparatus, nsk	
11	**334220**	**Radio and television broadcasting and wireless communications equipment manufacturing**	41,112
12		Other communication systems and equipment	
13		Broadcast, studio, and related electronic equipment	
14		Cellular handsets (cell phones)	
15		Wireless networking equipment	
16		Radio station equipment including satelite, airborne and earth-based (fixed and mobile)	
17		Antenna systems, sold separately	
18		Radio and TV broadcasting and wireless communications equipment, nsk	
19	**334290**	**Other communications equipment manufacturing**	1,035
20		Vehicular and pedestrian traffic control equipment, including electric railway signals and attachments	
21		Intercommunications systems, including inductive paging systems (selective paging), except telephone and telegraph	
22		Other Communications Equipment, nsk	
23	**334300**	**Audio and video equipment manufacturing**	12,294
24		Television receivers, including combination models	
25		Speakers, including loudspeakers systems and loudspeakers sold separately, and commercial sound equipment	
26	**334511**	**Search, detection, and navigation instruments manufacturing**	16,419
27		Search, detection, navigation, and guidance systems	
28		Search, detection, navigation, and guidance systems, nsk	
29	**335920**	**Communication and energy wire and cable manufacturing**	380
30		Telephone and telegraph wire and cable, made of nonferrous metals (purchased wire)	
31	**336414**	**Guided missile and space vehicle manufacturing**	119
32		All other services on complete space vehicles for other customers	
33	**517110**	**Wired Telecommunications Carriers**	7,712
34		Force account, telephone equipment installation	
35	**541300**	**Architectural, engineering, and related services**	6,084
36		Engineering services	
37	**S00402**	**Used and secondhand goods**	23
38		Used communication equipment	

Source: BEA Private Fixed Equipment Investment Bridge Table

messaging units, and fax machines) is removed.[1] Second, to obtain a telecom equipment price index that spans as many years as possible, the Byrne-Corrado results are spliced with a telecom equipment price index based on Flamm (1989) as complied by (Gordon, 1990, table 9.7, column 8) that begins in 1947. The Flamm-Gordon index does not include terminal equipment.

The resulting price index is shown on line 3 of table 2, a calculation that drives our main results. Note first, that because prices for cell phones drop more rapidly than prices for most other telecom products, the rate of decline in the telecom equipment investment price index shown on line 3 is less than that of the Byrne-Corrado spending index shown on line 10. Second, line 3 suggests that the pace of change in communications technology was swift in the immediate post-WWII period (column 1) but slowed

[1] Correspondence last year between the authors and BEA confirmed that BEA uses a 60 (household)–40 (business and government) ratio to split total spending on terminal equipment and cell phones. This split is apparently based on the Census Bureau's results for sources of wireline telecom carrier revenue by type of customer.

Table 2: **Communications Equipment Investment Price Index and Components (average annual percent change)**

		1947 to 1963 (1)	1963 to 1985 (2)	1985 to 2015 (3)	2010 to 2015 (4)
1.	Communications equipment, private fixed investment	-6.1	.9	-7.7	-9.8
2.	Equipment	-6.1	.9	-8.4	-10.3
3.	Telecom/data networking[1]	-6.4	.3	-11.6	-14.4
4.	Audio/video	-7.2	-3.2	-10.4	-14.3
5.	Broadcast and other	-1.1	2.9	-2.5	-2.6
6.	Search and navigation	-1.8	1.9	-3.8	-4.0
7.	Capitalized services[2]	–	–	-.8	-5.1
8.	Engineering	–	–	3.0	1.5
9.	Telecommunications[3]	–	–	-3.1	-6.6
Memos:					
10.	Byrne-Corrado NAICS 3342 spending[5]	–	.8	-12.3	-16.1
11.	Official BEA price index	.2	4.0	-2.7	-1.8
12.	Difference (row 1 less row 11)[4]	-6.3	-3.1	-5.0	-8.0

NOTES: Figures for 2015 are preliminary estimates. 1. Excludes consumer equipment. 2. Column 3 is from 1987. 3. Nonresidential component of NAICS 51711. 4. Percentage points. 5. Comprehensive spending price index including consumer equipment from Byrne and Corrado (2015a,b). Ending date is 2014.

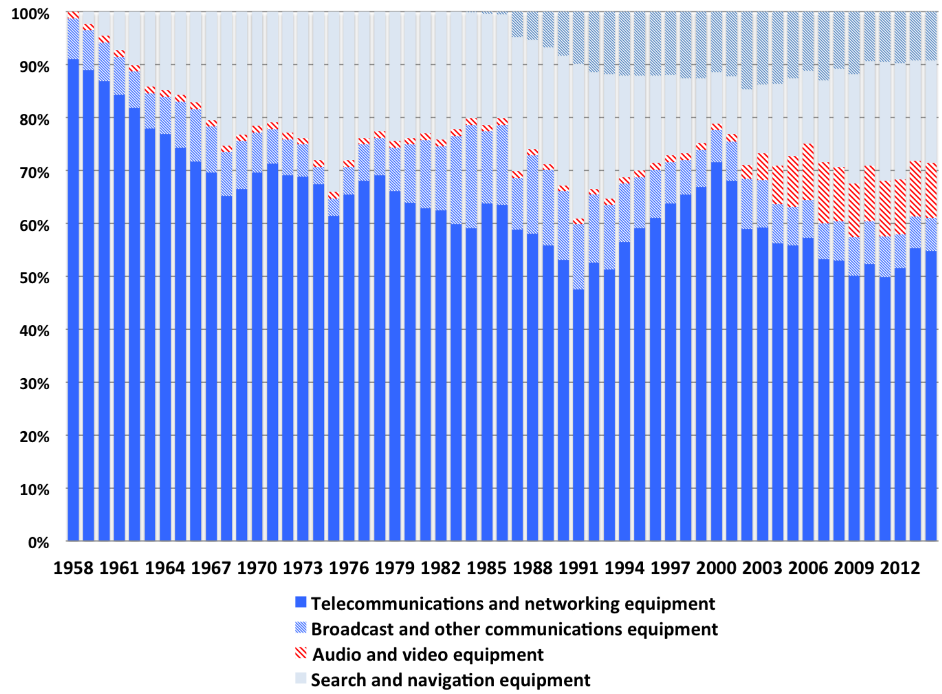
in the 1960s/early 1970s (column 2), as discussed by Flamm and Gordon and confirmed by Byrne and Corrado's more comprehensive estimates. As previously mentioned and reviewed in more depth in Byrne and Corrado (2015a,b), telecom equipment prices began to decline at a historically rapid clip after 1985 (column 3) and have been declining even more rapidly in recent years (column 4).

Audio and Video Equipment. Audio and Video (AV) equipment is a specific type of equipment included in communication equipment investment. The construction of a quality-adjusted price index for private investment in AV equipment from 1947 on is set out in table 3. As may be seen, a key ingredient to its history is a series developed by Gordon (1990). The bias implied by this series (4 percentage points per year) is carried forward in time even though certain findings suggest it could be increased: Gordon prepared a rough update of his earlier work (Gordon, 2015) and suggested price declines from 1985 to 2015 averaged 6 percentage points faster than the declines posted by the CPI. A matched-model calculation using detailed data from the Consumer Electronics Association for the years 2004 to 2008 yields price drops 11 percentage points faster than shown by the CPI for those years. Owing to the fragmentary and coarse nature of these findings, the bias is kept at the value implied by Gordon's long history.

The results for this AV equipment price index are shown on line 4 of table 2 and suggest a pace of change similar to that of telecom equipment.

Broadcast and other NAICS 3342 communications equipment. Byrne and Corrado did not study broadcast equipment in detail, but Hilbert and López (2011) compiled information on the world's technological effective capacity to broadcast and to telecommute information. From 1986 to 2007, based

Figure 2: **Communications Equipment Investment Shares by Asset Type, 1958 to 2014**



Note: Authors' elaboration of data from the U.S. BEA and Census Bureau.

on their estimates adjusted to exclude non-electronic broadcast means (e.g., newspapers), effective broadcast capacity grew at 1/4 the rate of growth in telecommunicate capacity (7.3 percent per year versus 29.6 percent). Although this result mixes demand (via use rates) and capacity and pertains to the entire world, it reveals a historically wide gap in the pace of change in these two means of communication.

Video compression, digital modulation, and forward error correction are key drivers of capacity increases in radio-wave based broadcasting (e.g., the more computationally complex the compression algorithm, the more video can be compressed). A recent analysis of U.S. broadcast capacity (satellite and cable) suggests digital video compression increased 7 percent per year through 2013 but was expected to accelerate 9-1/2 percent thereafter (Crowley, 2013). Convergence between video broadcasting and telecommunication services has been ongoing, and broadcasting quality is also improving along with better receiving equipment (i.e., TVs) and deployment of fiber.[2]

To construct quality-adjusted price indexes for this equipment grouping, a production cost index is constructed from 1947 on and a simple bias adjustment is applied to the pre- and post-1985 segments. Prior to 1985, the production cost index is the communication equipment price index BEA derived from regulatory information on costs (i.e., prior to adjustments for quality of equipment produced); PPIs are used from 1985 on, the year their initial availability. The bias adjustment is 25 percent of the difference between the rate of change of the production cost index and the rate of change of the quality-

[2]Convergence is also exemplified by the growth of digital TV services and video-on-demand. Statistics on the use of two-way video channels are not available, but according to a report from The Nielsen Company, over 40 percent of U.S. TV homes had subscription video-on-demand access service in 2014Q4. See `http://s1.q4cdn.com/199638165/files/doc_presentations/2015/total-audience-report-q4-2014.pdf`, accessed Febuary 8, 2016.

Table 3: **Sources and Methods Used to Estimate Price Change for Audio and Video Equipment**

Components of the index:	1947 to 1959	1960 to 1981	1982 to 1984	1985 to 2015
Television receivers	A	A	A	B
Speakers and other audio	D	C	C	C
Other equipment	D	D	E	E

Source data:

A	Gordon TV price index[a]
B	PCE price index for TVs (≈ CPI for TVs)
C	PCE price index for speakers
D	PPI for audio and video manufacturing
E	PPI for audio and video manufacturing, excl. TVs and speakers

Methods for TV component:

1947 to 1984	Series A
1985 to 2015	Bias-adjusted Series B; bias is -4.0 percentage points per year[b]

Methods for speaker and other audio component:

1947 to 1959	Series D
1960 to 2015	Series C

Methods for other equipment component:

1947 to 1981	Series D
1982 to 2015	Series E

Weighting:

Production weights for 1987 were developed from product shipments reported in the Census Bureau's Current Industrial Reports and Annual Survey of Manufactures and used to represent investment in all years. These shares are 68, 18, and 14 percent, respectively.

NOTES: a. Gordon (1990, page 306, table 7.19, last column). b. Bias is the average difference between changes in Series A and the CPI for TVs from to 1951 to 1984.

adjusted telecom equipment investment price index (e.g., the post-1985 adjustment is -3.3 percentage points per year).

Search & navigation equipment. Byrne and Corrado (2015a) did not study the search and navigation component of communication equipment investment in a comprehensive manner, but they did look at prices for GPS devices. A matched-model price index for GPS equipment built using detailed model-level data from The NPD Group and federal government (GSA) price schedules fell at a rate similar to overall telecomm equipment (13 percent) from 2003 to 2010.

GPS technology is fundamental to a substantial segment of the search & navigation equipment manufacturing industry, which sells 70 percent of its output to the U.S. Defense Department and long has been one of the U.S. economy's most technologically sophisticated sectors. Most of the industry's product shipments are for equipment and systems that arguably exploit the same advances in solid-state circuitry and radio wave transmission that lie behind the rapid change found for telecom equipment (which recall includes satellite communication systems).[3] Moreover, the search & navigation and computer and communications equipment industries are similar with respect to the share of intermediate inputs accounted for by electronic components (semiconductors), for which prices fall very rapidly (Byrne, 2015a). Information on defense/nondefense splits by detailed product line is not readily available, and with little further information to go on, we assume that 50 percent of nondefense purchases are for high-end equipment.

To construct quality-adjusted price indexes for this equipment grouping, the same procedure as that used for broadcast and other is used, only for search & navigation equipment, the bias adjustment is 50 percent of the difference between the rate of change in production costs and the rate of change of the telecom equipment investment price index. The bias adjustment for the post-1985 segment is -5.7 percentage points per year.

2.2 Capitalized services

Capitalized services are the systems design, engineering, and installation services associated with configuring and installing a new system of ICT equipment for a customer. Today's specialized markets for providing these services evolved from companies such as AT&T and IBM that included design and configuration services in the sales price of their manufactured systems. Capitalized services are included in ICT investment because they are part of the purchasers' price of a system whether such services are provided by specialists or original equipment makers. According to national accounting practice, however, only separately priced services are included as components with their own deflators (e.g., wholesale and retail services typically are not considered separately priced services).

For communications equipment, capitalized services consist of engineering services and telecommunications services used in installation. BEA introduced a separately priced component for engineering services in communication equipment investment in 1987 for which BEA documentation indicates that a PPI for engineering services has been used. More precisely, the commodity composition table (line 35 of table 1) suggests the BEA's price index for NAICS 5413 (which includes architectural as well as engineering services) is appropriate for this purpose. With regard to telecommunications services (line 33 of table 1), table 1 suggests a price index for wired telecommunications carriers (NAICS 517110) may be used.

A price index for the output of wired telecom carrier services from 1987 on was newly constructed for the Byrne and Corrado (2017) paper. Its nonresidential segment was used to deflate capitalized telecom services in the communications investment index, and results are shown on line 9 of table 2. The new price index incorporates information on prices of enterprise services from *Telegeography*; details of its construction are summarized in table 4 (page 8).

2.3 Shares

Shares in purchaser's prices are calculated from information found in BEA's "bridge" tables that map commodities to final demand. BEA provides this information for private equipment investment annually from 1997 on and in periodic benchmark I-O tables before then. The shares used to construct

[3] The high-end segment of search & navigation equipment includes reconnaissance and surveillance systems; radar systems and equipment; sonar search, detection, tracking, and communications equipment; specialized command and control data processing and display equipment; electronic warfare systems and equipment; and navigation systems and equipment.

Table 4: **Sources and Methods Used to Estimate Price Change for Wired Telecommunications Services (NAICS 51711)**

Components of the index:	1987 to 2001	2002 to 2006	2007 to 2014
Residential	A	A	A
Nonresidential	B	B	C, B

Source data:

A Price index for residential wireline telecom services, obtained by aggregating BEA PCE price indexes for internet access and wireline telephony (local and long-distance)

B BEA implied nonresidential price index obtained by chain-stripping Series A from BEA's gross output price index for wireline telecommunications carriers (NAICS 51711)

C Enterprise wireline services price index, this paper[a]

Methods for nonresidential component:

1987 to 2001 Series B[b]

2002 to 2006 Bias-adjusted Series B; bias is -5.2 percentage points wedged to 0 in 2001[c]

2007 to 2014 Weighted average of Series C (75 percent) and Series B (25 percent)[d]

Weighting:

Aggregation (and stripping) of components uses the net of own-use weights implied by the estimates shown in figure 6 of Byrne and Corrado(2017).

NOTES: a. Matched-model price index of *Telegeography* prices for four groups of enterprise business services (virtual private network; dedicated internet access; IP private line, domestic; IP private line, international). b. Series B for this segment is essentially identical to Series A. c. Bias is the average difference between changes in Series B and changes in the nonresidential price index from 2007 to 2014. d. Series B is used as the implicit price for non-enterprise nonresidential services for this segment; weighting is approximate.

the overall price index for communications investment uses detailed information from the 1963, 1967, 1972, 1977, 1987, 1992, and 1997, 2002, and 2007 benchmark tables, as well as the annual information from 1997 on. From 1987 on, this I-O information suggests that the telecom equipment share has been 60 percent of total investment spending, broadcast, AV and other equipment 11 percent, and search & navigation 19 percent. Capitalized services average 11 percent.

Prior to 1987 the situation is somewhat different: The telecom services share of communication equipment investment is much larger—it averaged 25 percent prior to the break-up of AT&T—but appears to have been partially offset by a larger wholesale margin after 1987. This is consistent with treating telecom services in the period prior to the early 1980s as an unpriced services margin. Capitalized services are therefore assumed to have edged from zero in the year after the break up of AT&T (1983) to the value (3.8 percent) reported for engineering services in its introduction year (1987). Subsequent years are interpolated values until 1997, when annual share information is available.

Equipment shares for telecom equipment and other equipment prior to 1997 are also obtained from the periodic bridge tables. Annual information on shipments of search and navigation equipment (nondefense) as well as detailed information in the Census Bureau's CIRs compiled in Byrne and Corrado (2015a) are used to interpolate the telecom/non-telecom equipment split where needed.

The estimated shares were previously displayed in figure 2.

3 Computers and peripheral equipment

This index is constructed using price indexes from the existing literature supplemented by bias-adjustments suggested by a reading of additional indicators of price-performance trends.

The U.S. BEA's detailed commodity composition of computers and peripheral equipment investment is reproduced in the figure shown on page 9. As in the case of communications equipment, the table is structured according to I-O item codes, which largely align with NAICS industry codes. Computers and peripheral equipment investment has both equipment and capitalized services commodity types.

We develop price indexes for the largest product lines in the electronic computer manufacturing category as shown in table 5—multiuser computers (line 2) and personal computers (line 3)–using the products for which research is available. In the case of multiuser computers, we employ an index for servers as a proxy for other types of multiuser computers, such as mainframes and supercomputers. In the case of personal computers, we employ and index for desktop PCs and notebook PCs as a proxy for other types of single-user computers, such as workstations and tablets. The computer storage device index is taken from Byrne (2015b) and is relatively comprehensive in scope. (Used equipment is "ignored", meaning it is effectively deflated by a weighted average of the price indexes for the other categories.) The estimated rates of change for the price indexes corresponding to key components are shown in the table on page 10 and shares of the key components in total computers and peripheral equipment investment are shown in the figure on page 14. A description of the derivation of these estimates follows.

Figure 3: **Commodity composition of computers and peripheral equipment investment**

	I-O item code	Equipment by type of product	2007 Value (millions of Dollars)
1		**Computers and peripheral equipment**	**87,725**
2	**334111**	**Electronic computer manufacturing**	50,365
3		Host computers, multiusers (mainframes, super computers, medium scale systems, UNIX servers, PC servers)	
4		Single user computers, microprocessor-based, capabale of supporting attached peripherals (personal computers, workstations, portable computers)	
5		Other computers, including array and other analog, hybrid and special purpose	
6		Electronic computers nsk, total	
7	**334112**	**Computer storage device manufacturing**	4,688
8		Computer storage devices (excl. parts/attachments/accessories/etc.)	
9		Parts, attachments, and accessories for computer storage devices	
10		Computer storage devices, nsk, total	
11	**33411A**	**Computer terminals and other computer peripheral equipment manufacturing**	14,266
12		Computer terminals (excl. parts/attachments/accessories/etc.)	
13		Computer terminals, nsk, total	
14		Input devices, all types	
15		Impact printers	
16		Nonimpact printers	
17		Digital cameras	
18		Optical scanning devices	
19		Monitors, accessories, and other peripheral equipment	
20		Other computer peripheral equipment, nsk, total	
21	**541512**	**Computer systems design services**	15,152
22	**S00402**	**Used and secondhand goods**	3,254
23		Used computing equipment	

Source: BEA Private Fixed Equipment Investment Bridge Table

Table 5: **Computers and Peripheral Equipment Investment Price Index and Components (average annual percent change)**

		1959 to 1985 (1)	1985 to 2015 (2)	1985 to 2010 (3)	2010 to 2015 (4)
1.	Computers and peripherals, private fixed investment	-18.0	-19.4	-20.7	-12.7
2.	Multiuser computers	-21.4	-22.5	-23.3	-18.5
3.	Personal computers	–	-26.4	-28.0	-18.0
4.	Storage equipment	-16.3	-26.7	-27.3	-23.4
5.	Other peripherals[1]	-13.0	-8.0	-9.3	-1.1
6.	Capitalized services[2]	–	-2.1	-1.8	-2.3
Memos:					
7.	Official BEA price index	-16.9	-11.6	-13.5	-1.6
8.	Difference (row 1 less row 7)[3]	-1.1	-7.8	-7.2	-11.1

NOTES: Figures for 2015 are preliminary estimates.
1. Includes terminals. 2. Column 3 is from 1987. 3. Percentage points.

3.1 Multiuser computers

Our analysis proceeds as follows. Multiuser computers (MCs) are divided into three classes—servers, mainframes and supercomputers—according to the role they play in the IT ecosystem. This allows separate discussion of computation, storage, transmission, and power consumption trends, which differ across classes. In contrast to PCs, for which highly granular price data are abundant, the information available for estimating quality-adjusted price trends for MCs is limited; consequently, we rely on judgmental adjustment of existing price indexes informed by data on engineering advances.

We adopt the price index employed in the national income and product accounts for the period from the late 1950s to the mid-1990s, a period for which research is robust.

In the 1980s, following on early work by Chow (1967), researchers at IBM conducted path-breaking research on multiuser computer prices in collaboration with BEA (Cole, Chen, Barquin-Stolleman, Dulberger, Halvacian, and Hodge, 1986). Price indexes were constructed based on list prices for IBM and IBM-compatible computer processors (CPUs) using hedonic regressions that accounted for key technical features as well as the disequilibrium in the market resulting from the dominant role played by IBM. Performance from a user value perspective was included in the form of million instructions per second (MIPS). Although MIPS does not control for the translation of those instructions into the performance of actual tasks, this nevertheless was likely a reasonable proxy for performance given the homogeneity of the computer market at the time. A composite hedonic/matched-model price index for multiuser computers (MCs) based on this research was introduced into the national accounts for 1969-1984 (Cartwright, 1986).[4] The indexes were later extended back to 1959 and updated through the mid-1990s.

The results for the BEA price index for MCs are largely corroborated by Gordon (1990) and Triplett (1989), and the computer price index shown in table 5 adopts the BEA MC index through 1996.

[4]Composite hedonic indexes aggregate item prices using a matched-model approach, but for periods where an item has just appeared in the sample, prices imputed by hedonic regression are used to construct relative prices. Triplett (1989) notes that this approach is theoretically equivalent to the time-series regression approach more commonly used in academic research, where time dummies are chained together to generate a price index.

MCs in the national accounts are deflated from 1996 forward by the Bureau of Labor Statistics (BLS) producer price index (Grimm, Moulton, and Wasshausen, 2005). For this period, we use the server price index as discussed below.[5]

Servers. Servers traditionally focussed on providing a single function for client computers, such as managing print resources, processing email, or delivering web pages.

Monolithic multi-user computers, most notably mainframes, accounted for the bulk of the commercial MC market from its inception until the mid-1980s. A surge in PC investment and networks to connect them–including both local networks and the internet–followed in the 1990s, raising the importance of servers providing data, communications, and applications to PC clients. Data from a high-tech consultancy (IDC) suggest that servers now account for about 80 percent of total MC investment.

Not surprisingly given the importance of servers and the difficulty noted here of measuring prices and quality for other types of MCs, servers appear to be the sole focus of the PPI.[6] Hedonic regressions are estimated by BLS for servers annually with an extensive set of control variables for technical features, such as the amount of memory, and for engineering performance, such as clockspeed. However, there is reason to believe that the specifications employed may not adequately account for performance trends. In particular, no controls are used for directly-measured efficiency of user task completion, which may be problematic in light of the divergence between clockspeed and performance trends that opened up in the early 2000s (Byrne, Oliner, and Sichel, 2017a).[7]

To address this concern, we examine system performance trends. From 2002 to the present, we use scores from by the widely-referenced benchmark scores published by Systems Performance Evaluation Corporation (SPEC).[8] Specifically we employ the median SPEC performance for systems employing Intel Xeon processors, which dominated the server market in that period.[9] For performance in earlier years, we use price per million floating point operations (megaflops) reported in Hilbert and López (2011) which extend through 2007. The Hilbert and López-based series has a similar contour to the SPEC-based series but falls about 4 percentage point faster in the overlap period. Because the SPEC score is based on a suite of user applications, we prefer that index and extrapolate it back to 1995 using the Hilbert and López series adjusted for this bias.

We use the performance index to quality-adjust a server unit price series constructed using data from high-tech consultancies (Gartner and IDC) on revenue and units for the U.S. market available beginning in 1996. In particular, we divide U.S. server revenue by the product of U.S. unit sales and our performance index. Beginning in 1997, our indicator falls markedly faster than the PPI, with an average difference of 20 percentage points (figure 4). For our final index, we blend our indicator with the PPI, assigning 1/3 weight to the PPI. We combine the indexes because each has distinct merits. We have concerns about the control for computing performance in the PPI, but we also note that the PPI controls for other important features of servers such as the operating system, memory, and

[5]The BLS producer price index (PPI) also uses a hybrid hedonic/matched-model approach. See `http://www.bls.gov/ppi/ppicomqa.htm` (dated June 2011, accessed July 1, 2016) for illustrative examples of BLS hedonic regressions and quality adjustment of computer prices.

[6]We deduce this from the fact that BLS doucumentation provides the specification for a regression used in 2011 that only references Xeon MPUs, which suggests that mainframes, which do not use Xeons, are not in scope.

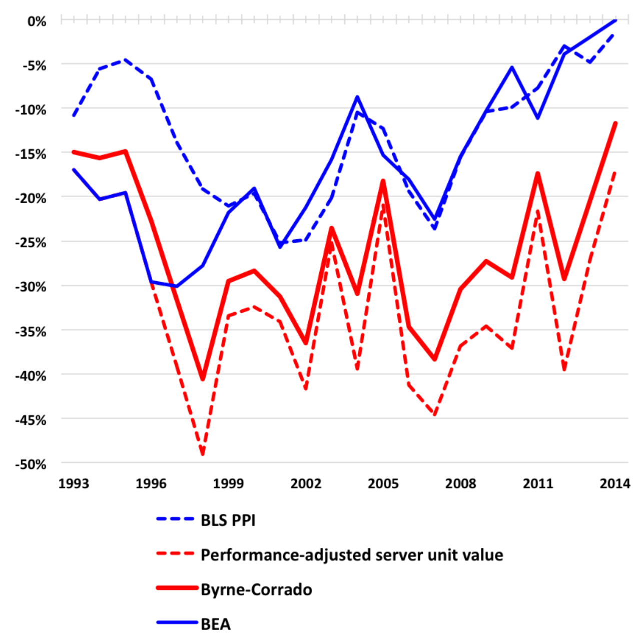
[7]The absence of direct measures does not necessarily imply that quality-adjustment is inadequate if a linear combination of technical features predicts performance.

[8]Scores for SPEC® CPU2006 and SPEC® CPU2000 retrieved from `http://www.spec.org` on June 6, 2016. Comparison between the two benchmark suites based score ratios for models reporting results for both.

[9]The BLS hedonic regressions for servers also concentrate exclusively on Xeon processor systems.

interconnect technology.[10] Our final index, a blend of the indicator and the PPI, falls 11 percentage points faster than the BEA investment index. (Note that the BEA investment index is a weighted average of the BLS PPI and the BLS import price index.)

Figure 4: **Alternative server price indexes (percent change), 1993 to 2014**



Mainframes. Mainframes are designed to rapidly handle a diverse and shifting workload of computational tasks—especially business transactions, loosely defined—in a highly secure, fail-safe environment. For mainframes, the analysis is confined to IBM, long the most relevant and dominant player in the market.[11] IBM publishes performance scores for its systems whose usefulness is enhanced by two features: they are based on time to complete commonly used applications (rather than an artificial basket of instructions) and IBM is deeply committed to backward compatibility, making comparisons over time informative. Table 6 below shows benchmark scores, known as Large System Performance Reference ratios (LSPRs), for IBM's flagship mainframe models.[12] Our goal with this table is a simple examination of the pace of advance of the frontier for mainframes in the "enterprise" (i.e., large business) market.

In the mid-1990s, six generations of mainframes using the System/390 architecture were introduced in quick succession and performance shot up 90 percent per year. In the 2005–2015 period, a series of mainframes known as the zSeries was released for which performance rose 18 percent per year on average. This performance slowdown may well reflect the challenges that emerged in single-core performance as excessive heat generation restrained the pace of increase in processor clockspeed; as is

[10] In some cases, the server PPI controls for power consumption as well, a crucial consideration. (Conversation with Fred Merkel, BLS April, 2016.).

[11] The IBM System 360 line of mainframes had a 65 percent market share in 1977. Competitors, such as Amdahl and Hitachi, primarily produced systems intended to mimic IBM.

[12] See `https://www-304.ibm.com/servers/resourcelink/lib03060.nsf/pages/lsprindex/$file/SC28118719.pdf` (accessed July 1, 2016) for more information on LSPRs. Models fully loaded with processors are chosen for this analysis.

Table 6: **IBM Enterprise Mainframe Prices and Performance Scores**

Model	Year	Processors	Performance	Price	Price/Perf.
System/390:					
G1	1994	6	1.1	1,260,000	1,200,000
G2	1995	10	2.7	2,550,000	940,959
G3	1996	10	5.9	3,600,000	607,083
G4	1997	10	7.1	3,240,750	457,733
G5	1998	10	17.6	4,000,000	227,015
G6	1999	10	26.1	4,842,000	185,588
Annual growth rate			90%	31%	-31%
zSeries:					
Z9	2005	54	39.6	22,251,000	562,462
Z10	2008	64	50.9	25,949,995	509,523
Z196	2010	80	93.4	28,546,000	305,632
EC12	2012	101	140.1	33,096,000	236,231
Z13	2015	141	199.3	n/a	n/a
Annual growth rate			18%	6%	-12%

NOTES: System/390: Large-scale Performance Ratio for OS/390 operating system, indexed to performance of System/390 Series G4 9672 R15 = 1.
zSeries: Large-scale Performance Ratio, Multi-Image (MI) for z/OS operating system, indexed to System z9 2094-701 = 1. z13 score is extrapolated using ratio z13 Performance Capacity Index (MIPS) to EC12.

apparent in the rise of the number of processors used, IBM turned increasingly to parallel processing to deliver greater performance.

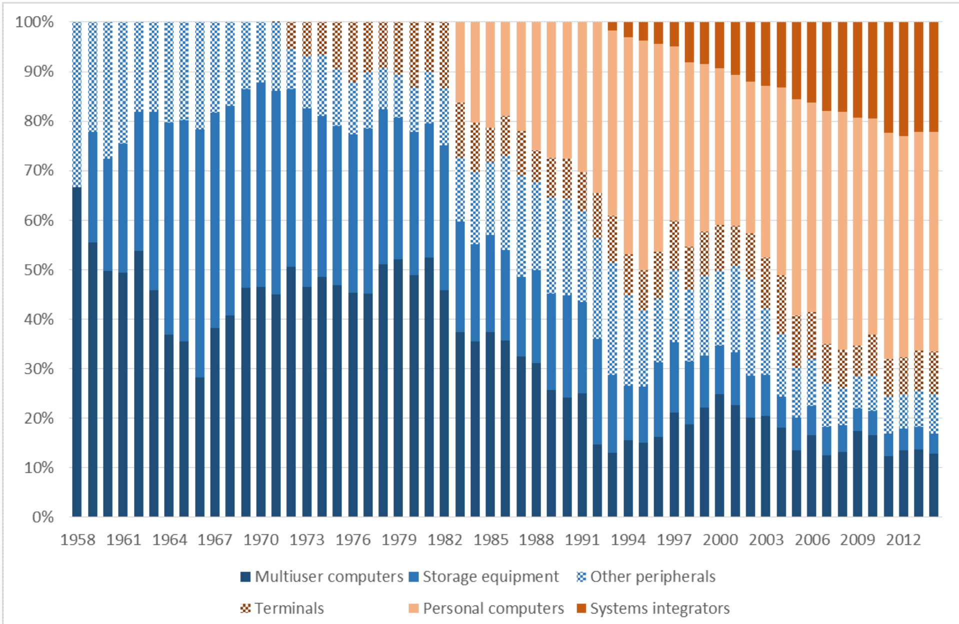
Prices for selected IBM mainframe models from 1990 to 2012 were obtained from an analyst's compilation available online.[13] Only prices on introduction are available and we do not have relative importance weights or an exhaustive set of model characteristics.[14] Table 6 shows that prices rose substantially less than performance in both periods. The price-performance ratio fell 31 percent per year for System/390 frontier models in the late 1990s, but by a more moderate 12 percent per year for zSeries models from 2005 to 2012.

These results are not comprehensive and should be interpreted with caution. Also, it is important to note that IBM's business model is focused on the joint sale of hardware, software and services using long term contracts, and quality-adjusting prices is difficult without information on the terms of sale. That being said, the index for frontier mainframes in the late 1990s falls about 30 percent per year, then slows to a bit more than 10 percent per year in the latter part of the first decade of the 2000s. Interestingly, these rates fall on either side of the roughly 20 percent average rate of decline of the BEA mainframe investment index from 1959 to 1995, suggesting that this long-run trend has persisted on average, though the recent slowing is substantial and the outlook is unclear. BEA has not conducted research on mainframe prices for its official computer index since the early 1990s. The BLS PPI was adopted by BEA for deflating MC investment at that point and as noted previously, that index appears to be based exclusively on servers.

[13] See Technology News, `http://www.tech-news.com`. We thank Hesh Werner for generously providing these data to the public and for guidance on interpreting the IBM mainframe market.

[14] In ongoing work, we match these prices to characteristics and update the results of Cole et al. (1986) through 2012.

Figure 5: **Computers and peripheral equipment investment shares by asset type, 1958 to 2014**



Note: Authors' elaboration of data from the U.S. BEA and Census Bureau.

Supercomputers. Supercomputers are used to solve immense computational problems, such as simulating complex phenomena (e.g., weather) or processing seismic data for geological exploration, using massively parallel architecture. Although we do not have the information to construct a deflator for investment in supercomputers, recent trends in performance are examined to shed light on the pace of technical change in advanced computing and adoption by industry. Supercomputers account for 5-10 percent of MC spending.[15] Performance—as measured by the speed of inversion for a very large matrix with the *LINPACK* benchmark—of the top U.S. supercomputer rose 75 percent per year on average from the inception of the Top 500 list in 1993 to 2015, but since 2000 there have been two distinct periods (Byrne and Corrado, 2016, table 2, line 24). From 2000 to 2008, performance of the median Top500 computer rose 95-1/2 percent per year, but has slowed to 55.2 percent per year since then. Performance of the median U.S. *industrial* supercomputer appearing on the TOP500 list, rises at the same pace as the overall median, on average, but typically attains the level of performance of the concurrent leading edge machine five years later.

The slowdown in computational performance gains at the leading edge and for industrial machines is striking. This apparent regime change may be attributable to increasing challenges with power consumption that emerged in the mid-2000s. This led to a shift of focus away from raising the speed of individual processors and toward greater reliance on use of processors in parallel and experimentation with more energy-efficient processors, such as graphics processing units (GPUs) and "embedded" MPUs. These architecture changes have paid off in greater power efficiency. The median megaflops-per-Watt score for supercomputers as recorded the The GREEN500 list of the world's most energy-efficient supercomputers (also available at `http://www.top500.org`, rose 47 percent per year from 2012 to 2015, a notable step-up from the previous pace of 34 percent since the inception of the list in

[15] Gartner estimated U.S. supercomputing spending of roughly $2 billion per year in the early 2000s, which includes the federal government and universities. According to the TOP500 list of high-performance computers (`http://www.top500.org`), however, about 2/3 of US supercomputers on the global top 500 list were industrial.

2007.[16] Payoffs to the GPU-based architecture in terms of calculation performance require new systems and new programming tools and thus may take longer to arrive than gains previously associated with better and faster CPUs.

3.2 Personal computers

Desktop personal computers (PCs) emerged as a significant share of U.S. computer investment beginning in the mid-1980s, followed by portable personal computers (laptops or notebooks) in the late 1990s.[17] The emergence of PCs as an important business tool has led to a situation in which the PC price index has notable impact on the overall computer investment deflator.

BEA introduced a PC price index covering 1982–1987 in 1988 (Cartwright and Smith, 1988). The agency maintained this index until adopting the BLS composite hedonic/matched-model price index (Sinclair and Catron, 1990) that begins in January 1992. More precisely, BEA's annual PC investment price index is a chain-weighted average of the BLS PPI and the BLS import price index (IPI) for computers from 1993 on.

The ready availability of data and interest in the role of the PC in productivity has led to a host of studies of PC prices. As acknowledged in Landefeld and Grimm (2000) and the review in Berndt and Rappaport (2001), price indexes from some outside studies fall significantly faster than the BEA PC price index. One study cited was an early version of results reported in Berndt and Rappaport (2003) and is the basis of the PC price index shown on line 8 of table 1. Compared with earlier research, Berndt and Rappaport (2003) use a very flexible form for the hedonic function that relates prices and characteristics of PCs. They include dummies for processor type and interactions of those dummies with clock speed to allow the regression to better account for the rapid increase in MPU performance in the 1990s.

Berndt and Rappaport (2003, hereafter BR) adjacent-year laptop and desktop price indexes are used to develop the history for the price index shown on line 8 of table 1. Specifically, the adjacent year indexes reported in BR table 3 with flexible processor controls that cover 1989 to 2003 are extended back to 1983 using the adjacent-year indexes reported in BR table 2; the indexes are smoothed using a three-year moving average. The smoothed laptop and desktop indexes are aggregated using platform investment shares constructed with consultancy data (IDC and Gartner) beginning in 1992 and using CIR (production) detail in prior years.

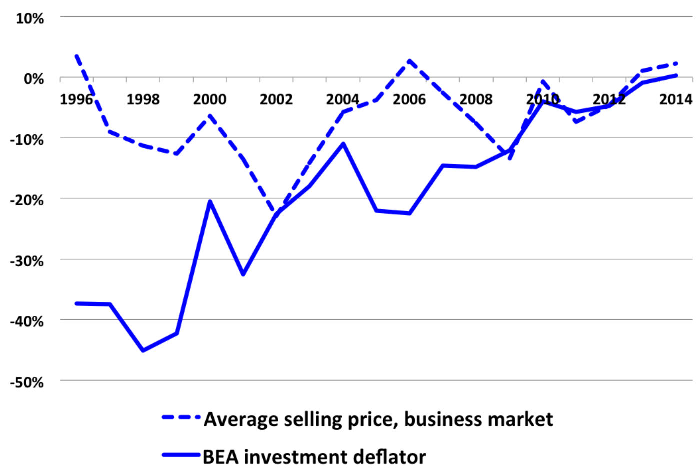
Recent research shows that the performance of MPUs for PCs is not well proxied by clockspeed and other technical features in hedonic regressions after 2002, and that direct (benchmark) measures of performance are needed to fully adjust for performance (Byrne et al., 2017a). The BLS hedonic analysis of PCs relies primarily on engineering features and does not employ benchmarks, and the gap between the BEA investment index and average prices has dwindled appreciably since the late 1990s (figure 6). Indeed, the average price of a PC sold in the U.S. business market fell 5 percent per year on average from 2010 to 2015, the same rate as the decline in BEA PC investment price index, indicating the BEA is picking up no quality improvement in PCs over that time period.

[16]Looking at the broader computer industry, Koomey, Berard, Sanchez, and Wong (2011) report that power efficiency has historically grown 26 percent per year, implying that the recent efficiency gains for supercomputers have been very rapid in comparison.

[17]Tablet computers have risen in importance since 2010 and are not addressed in this analysis. Byrne, Oliner, and Sichel (2017b) and Byrne, Dunn, and Pinto (2016) estimate price indexes for tablets, but this work is preliminary.

To adjust the PPI for improvements in quality due to increases in performance, we add the difference (20 percentage points) found by Byrne et al. (2015) between MPU hedonic indexes accounting for quality and indexes that do not times the approximate cost of MPUs as a share of PC value (15 percent) to arrive at a correction to the PPI (3 percentage points per year from 2002 on). The corrected PPI is used as PC investment price deflator from 2003 on.[18]

Figure 6: **Personal computer price change, 1996 to 2014**



Source. IDC, Inc.; Bureau of Economic Analysis

3.3 Storage, other peripherals, and capitalized services

For storage equipment, the official BEA investment price is a weighted average of the BLS PPI and import price index. This index falls roughly 20 percentage points slower than a measure of price per megabyte for hard drives developed and updated by McCallum (2002) from 1985 to 2014.[19] Work by Byrne (2015b) uses model-level prices for storage equipment to create a matched-model price index that falls at nearly the rate of the raw price-per-megabyte series from 2002 to 2014. From 2002 forward, we use the Byrne (2015b) index. We use the BEA investment price index for storage equipment from 1958 to 1984 and from 1985 to 2001 use the geometric mean of this index and the McCallum price-per-gigabyte series.

Very little research has been conducted on price trends for other computer peripherals. Although Cole et al. (1986) and subsequent extensions were based on hedonic analysis, the BLS price indexes employed in BEA investment deflators from the early 1990s forward use standard matched-model techniques without hedonic adjustment. Although in principle the standard methodology could capture quality change, Aizcorbe and Pho (2005) estimate price indexes for a range of peripherals using NPD model-level scanner data and report prices that fall substantially faster than the BLS PPI. This work is suggestive but only covers a three year period, which we view as insufficient to justify bias-adjusting the official investment index.

[18]The shortcomings of BEA's procedure of averaging the PPI and the IPI are set out in Byrne and Pinto (2015).

[19]Updates can be found at `http://www.jcmit.com/diskprice.htm`.

Table 7: **Sources and Methods Used to Estimate Price Change for Computers and Peripheral Equipment**

Methods for multiuser computer component:	
1959 to 1996	BEA investment price deflator for "mainframes"[a]
1997 to 2015	Weighted average of quality-adjusted server unit value (2/3) and BLS PPI for "host computers, multiuser (mainframes, medium scale systems, Unix and PC servers)" (1/3).
Methods for personal computer component:	
1983 to 1988	Chained adjacent-year hedonic indexes for desktop and mobile PCs[b], Berndt and Rappaport (2003) table 2.
1989 to 2003	Hedonic estimates w/ flexible MPU speed/family interactions, Berndt and Rappaport (2003) table 3.
2004 to 2015	U.S. revenue-weighted average of BLS PPIs for "portable computers, laptops, PDAs and other "single-user computers" and for "personal computers and workstations (excluding portable computers)," bias-adjusted using MPU index bias from Byrne et al. (2017a) by authors' estimate of MPU input cost share for PCs.
Methods for storage equipment component:	
1959 to 1984	BEA investment price deflator for "storage devices."
1985 to 2001	Equal-weighted average of BEA investment deflator and price-per-megabyte series based on McCallum (2002).
2002 to 2015	Byrne (2015b) as extended by Federal Reserve Board.[c]

Weighting:

Investment weights for computers (as a whole), storage equipment, other peripherals, and systems are from BEA's "Detailed Data for Fixed Assets and Consumer Durable Goods", available at `https://bea.gov/national/FA2004/Details/Index.htm`. BEA formerly published further detail on investment by type of computer beginning in 1995, including PCs (as a whole) and MCs, in a spreadsheet entitled "Final Sales of Domestic Computers". These data were extended to 2015 using reports on U.S. sales from IDC, and backward to 1977 (the emergence of PCs) using domestic production by product from Census Current Industrial Reports. Investment weights for portable and other personal computers is based on U.S. sales shares from IDC for 1995–2015 extrapolated from an arbitrary portable revenue share of 2% in 1981 to 1995 using a fixed growth rate.

NOTES: a. "Mainframes" in BEA nomenclature refers to all multi-user computers. b. Investment in workstations is deflated by price index for desktop PCs; investment in luggables, laptops, notebooks, and tablets is deflated by price index for "mobile" PCs; smartphones are classified as communications equipment. c. Available at `https://www.federalreserve.gov/releases/g17/ComputerStoragePriceIndex.htm`

The price index for custom software investment, whose corresponding NAICS industry is 541511 (custom computer programming services), is used as the price index for the capitalized services component of computer investment, NAICS 541512 (computer systems design services). The construction of the price index for custom software is described in the following section.

3.4 Shares

The shares used for aggregating the component price indexes into an investment index for computers and peripheral equipment are found on the BEA website under "Detailed Data for Fixed Assets and Consumer Durable Goods" (`https://bea.gov/national/FA2004/Details/Index.htm`). We use the nominal weights included in the "Investment in Private Nonresidential Fixed Assets" table. This table is not included in the standard fixed asset tables because "the detailed estimates are more likely to be either based on judgmental trends, on trends in the higher level aggregate, or on less reliable source data." That being said, the broad contours of these series are quite similar, so the contour of the overall price index for computers and peripheral equipment is not likely to be driven by the weighting scheme.

4 Computer Software

This index is constructed using the basic approach used by BEA but a different structure is introduced. The novelty in the structure is that it includes an explicit enterprise software component consisting of systems and applications software components. As of the writing of this paper, neither desktop nor enterprise systems software are included in BEA's investment price index for software.

What do we know about systems software? Greenstein and Nagle (2014) looked at the economic benefits of Apache, a widely-used open source software system used to manage e-commerce transactions in the 1990s, and found substantial benefits even after accounting for substitution with priced products. This suggests there could be large price declines in the systems software in wide use today, but we cannot really know without additional research. The PPI does not disclose its index for systems software, but we calculate an implied index as detailed below. This implied index in fact drops relatively rapidly, and while its incorporation in an ICT asset price index is a major step forward (it has a large weight), its impact on the new price index for enterprise software is partially offset by the rising PPI for enterprise and network application software. All told, much additional research is needed to further improve the new price measures for enterprise application and systems software developed in this paper.

The U.S. BEA's software price index has three components:

- Prepackaged software products (hereafter, software products),
- Custom programmed software, and
- Software produced on own-account.

where own-account software is specialized software developed or improved in-house rather than purchased as custom-made software from a software development company. The relative proportions of these components were shown in figure 7 (b) of Byrne and Corrado (2017).

BEA's approach to measuring current prices for these components may be summarized as follows:

- The price index for software products from 1998 on is a bias-adjusted BLS PPI for *application* software publishing; prior to 1998, a research price index is used.
- The price indexes for custom and own-account software prices are productivity-adjusted input cost measures, where productivity in custom and own-account software production is essentially 1/2 that of productivity in software products production.

The BEA approach was developed by Parker and Grimm (2000), who opined "...the information available on price indexes for prepackaged software is limited, and no price indexes are available for the prices of custom or own-account software." Information on software products was limited in that most of the research available to Parker and Grimm pertained to PC desktop application software—this situation has not changed.[20] Nor has the fact that the industry whose subcomponent largely reflects purchases of custom programmed software (NAICS 5415) remains out-of-scope in the BLS PPI.

For the software price index developed for this paper, the BEA's basic approach is retained but four steps are taken to improve it:

- A more granular structure is developed for the software products index.
- Information on *system* software prices is incorporated in the software product price measures.
- The BEA bias adjustment to the PPI is updated based on research available subsequent to Parker and Grimm's work.
- The input cost measure used by BEA for the custom and own-account components is refined to reflect capital costs as well as wages of programmers.

Further details follow.

4.1 Software products

The sources and methods used to construct this index are summarized in table 8. There are two major categories to this index: (1) desktop and portable device software, and (2) enterprise and related software.

Structure and coverage. The Census Bureau uses two classification schemes to present its data on software. In each scheme, the high level components are application software and systems software.

In the periodic economic census, application software consists of:

- general business productivity and home use software
- game software
- cross-industry application software
- vertical market application software
- utilities software
- other application software

whereas system software consists of:

[20] One study available to Parker and Grimm (Harhoff and Moch, 1997) covered a PC database platform for business applications, but prices for PC desktop operating systems were not studied until much later (Abel, Berndt, and White, 2007; Copeland, 2013).

- operating systems software
- network software
- database management software
- development tools and programming languages
- other system software.

In the annual surveys, application and system software are *each* disaggregated according to platform:

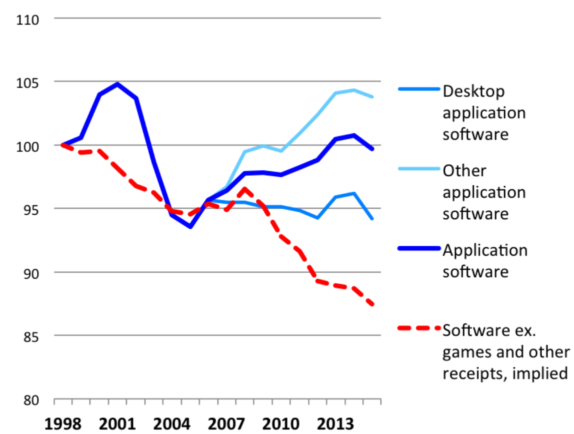
- personal computer software
- enterprise or network (i.e., server) software
- mainframe computer software
- other application/system software.

The table below figure 7 shows the structure the BLS has used for its software products PPI (NAICS 5112) since 2006. As may be seen, the BLS is using a blend of the Census schemes in presenting its software products price index. The blended structure is useful for building an investment price index because it strips out games, which are products purchased almost exclusively for home use. Annual data on game software sales are not reported in the Census Bureau's Services Annual Survey.

The software PPI structure table highlights that a price index for software *products* excluding games is not issued by the BLS. A price index for application software products (excluding games) is published, but the BLS price index for system software does not meet the agency's standards for disclosure and therefore is not published. Price developments in a very important area of software product development are therefore (unintentionally) obscured: cloud computing platforms are enabled by systems software, high performance computing is enabled by specialized systems development tools; big data analytics are enabled by database management software, etc.

Because a price index for software products excluding games is the most relevant driver of a software products investment price index, an implied BLS price index for this and its systems software component are calculated from 1998 on.[21] The bottom line is that BEA has been using the dark blue line in figure 7

Figure 7: **BLS software price indexes, published and implied, 1998=100**



Structure of BLS Software PPI

1.	Software publishing, except games
2.	*Software, except games and other receipts*
3.	Application software publishing
4.	Desktop and portable device apps
5.	Enterprise and other apps
6.	*Systems software publishing*
7.	*Desktop and portable device systems*
8.	*Enterprise and other systems*
9.	Other receipts
10.	Game software publishing

Note: Price indexes on lines 2, 6, 7, and 8 are not disclosed.

[21] Note that the calculations used to create the implied price indexes for software products excluding games and systems software are sensitive to the weights used. Furthermore, the calculations entail a series of steps because the PPI for software publishing excluding games only begins in 2006 and the components of the application software PPI also changed in that year. Weights for games, other receipts, and system software are needed to calculate the relevant price indexes from 1998 on and were obtained from the periodic economic censuses from 1997 on. Because weights from

to drive its investment software price index, whereas the index set out in table 8 is driven essentially by the dashed red line. In fact, the implied systems PPI is used directly and aggregated with appropriate annual weights, not the lagged census weights used to construct the PPI (see previous footnote).

Systems software averaged 49 percent of total software products excluding games from 2010 to 2014 according to the 2014 Services Annual Survey.[22] The largest component within both systems and application software is enterprise and mainframe software, which rose from 62.6 percent of total software products excluding games in 2010 to 66.5 percent in 2014. This increase is driven by movement within the system component—sales of systems software for personal computers were lower in 2014 than they were in 2007.

Information on prices for desktop vs enterprise/other components of system software is unavailable. For this reason, and also because desktop system software does not loom very large in total desktop software (as well as in total system software), software investment price change is built from the three available component measures from 2007 on (desktop application, other application, and system software) where desktop application software prices are used to represent all desktop software prices, and all system software prices are used to represent enterprise system software prices. Prior to 2007, the three components are estimated using methods consistent with the methods used to develop BEA's existing history.

Bias adjustment. When Parker and Grimm developed BEA's current approach, experience with BLS's software PPI was very limited (the series began in January 1998). The bias adjustment they recommended (-3.15 percentage points per year) was thus based on limited information. On the basis of subsequently available work, including PC desktop operating systems software (Abel et al., 2007; Copeland, 2013), the bias adjustment has been changed, to -4.15 percentage points per year. The adjustment is based on the difference between a spliced research series for PC productivity and O/S software and BEA's existing series (the application software PPI adjusted by -3.15 percent per year) from 1998 to 2003, i.e., the research series fell 1 percentage point per year faster from 1998 to 2003.

Strictly speaking, the newly calibrated bias adjustment pertains only to the desktop component of software products investment, but it is used for the other components due to lack of other pertinent information. Not only are there no recent studies of software prices, there are no studies of enterprise, mainframe, or server software prices, period—making it next to impossible to determine whether the software products that power today's mobile and cloud business platforms are being adequately captured in our price statistics.

periodic censuses become available with a lag, to correspond with the PPI, the calculations used to construct the implied price indexes including system software employ 1997 weights beginning 2004, 2002 weights beginning 2008, and 2007 weights from 2012 on. Owing to the lack of detail in the 1992 census, 1997 weights are used in lieu of actual weights for this period.

[22] Game software is not separately reported in annual surveys. Game software sales are assumed to be included in the "other application software" category, and annual estimates for game software sales were based on the 2012 economic census and press reports issued by NPD.

Table 8: **Sources and Methods Used to Estimate Price Change for software products investment**

Components of the index:	1959 to 1985	1986 to 1998	1999 to 2006	2007 to 2015
Desktop and portable computer device software	–	A	B	C
Enterprise and server/mainframe software	D	D	–	–
Applications	–	–	B	E
Systems	–	–	F	F

Source data:

A BEA prepackaged software price index derived from research estimates of prices for selected types of PC desktop application and database software (Parker and Grimm, 2000)
B BLS application software price index (excluding games)
C BLS desktop and portable device application software price index
D BEA prepackaged software price index based on .6 times hardware price change[a]
E BLS other applications software price index
F Implied BLS systems software price index, this paper

Methods for desktop component:

1986 to 1998 Series A
1999 to 2006 Bias-adjusted Series B; bias is -4.15 percentage points per year[b]
2007 to 2014 Bias-adjusted Series C; bias is -4.15 percentage points per year[b]

Methods for enterprise components:

1959 to 1998 Series D
1999 to 2015 Bias-adjusted Series B, E and F, depending on segment and component, where the bias is -4.15 percentage points per year

Weighting:

Desktop and enterprise components are weighted based on information on the composition of domestic sales from the Census Bureau from 1997 on and from trade reports for prior years. The sub-components of the enterprise price index are equally weighted.

NOTES: a. The hardware price index is BEA's computer price index to 1994 and this paper's server/mainframe and data networking price indexes from 1995 on (equally weighted). b. Bias is the average difference between changes in Series B and changes in a research price index available from 1998 to 2003. The research price index links matched-model price indexes for PC desktop productivity and O/S software developed by Abel et al. (2007) and Copeland (2013).

4.2 Custom and own-account software

The BEA currently applies a productivity adjustment to programmer wage costs whereas using the combined costs of programmer labor, capital, and intermediate inputs is a more appropriate approach. There are at several drawbacks to pursuing the more theoretically appropriate approach. First, precise information on the capital and intermediate input costs of custom programming firms and own-account software production within firms is unavailable. Second, even if industry-level measures of combined input costs were to be used as a relevant approximation of the unobserved combined costs, such measures usually are extremely volatile. Indeed, BLS estimates of the combined input costs for the software products and computer design services industries (NAICS 5112 and NAICS 5415, where NAICS 5415 includes custom programming services) are found to be rather volatile. Third, while the

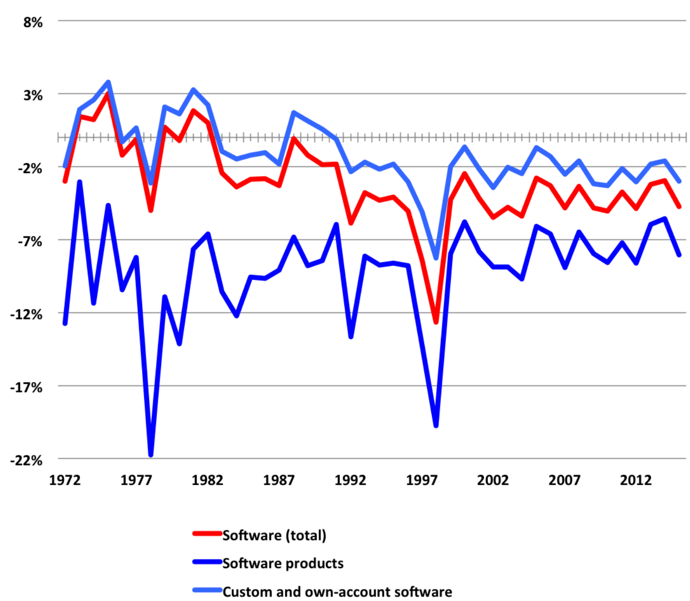
BLS makes use of essentially all available data, their estimates begin in 1987, and it is necessary to have price deflator for (own-account) software that begins in 1959.

Two steps are taken to circumvent these drawbacks: (1) Changes in the GDP deflator are used as a combined cost indicator. The trend in the average (log) change in BLS's combined cost indexes for NAICS 5112 and N5415 industries is essentially the same as the trend in the GDP price deflator from 1987 to 2010. (2) To tie the indicator more closely to computer program development costs, changes in the GDP deflator are averaged with changes in programmer wages.

The BEA assumption that custom and own-account software output is produced with 1/2 the efficiency of mass-marketed software products is retained, that is, the final custom and own-account price index is an average of changes in the combined cost indicator and the software products price index.

Results are shown in figure 8.

Figure 8: **Software and software components price change, 1972 to 2015**



5 Conclusion

This paper supplements our recent paper "ICT Services and their Prices: What do they tell us about Productivity and Technology?" by providing detailed descriptions of the construction of the alternative national accounts-style ICT investment price deflators that are reported and analyzed in that paper. The ICT equipment prices described herein were also used in Byrne et al. (2016).

As seen in columns 2 and 3 of table 1, according to our estimates, the understatement of the pace of change in ICT asset prices is substantial. Declines in ICT investment prices are estimated to have been 10.6 percent per year from 1987 to 2003 and 8.0 percent per year from 2004 to 2015 (4.2 and 5.9 percentage points per year faster, respectively, than official estimates). Further implications are explored in the above-cited papers.

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